LHC Higgs diphoton signal interference with background

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LHC vs. SUSY in 2010: Eagerly confronting our fate.

LHC vs. SUSY in 2011: Just a flesh wound.

LHC vs. SUSY in 2012: Uh-oh. Now it is serious.

But I suspect that’s wrong, and SUSY isn’t like the Black Knight of Monty Python.

Instead, perhaps SUSY is the French Knight of Monty Python, in a high and secure place, taunting us:

What we’ve learned in 2012:

- Higgs-like object exists at $M_H \approx$126 GeV
- It looks consistent with Standard Model Higgs
- No new physics associated with non-Standard-Model-ness of the EWSB sector is apparent (??)

Therefore, it is sensible to assume that this is indeed the Standard Model Higgs, and nothing more.

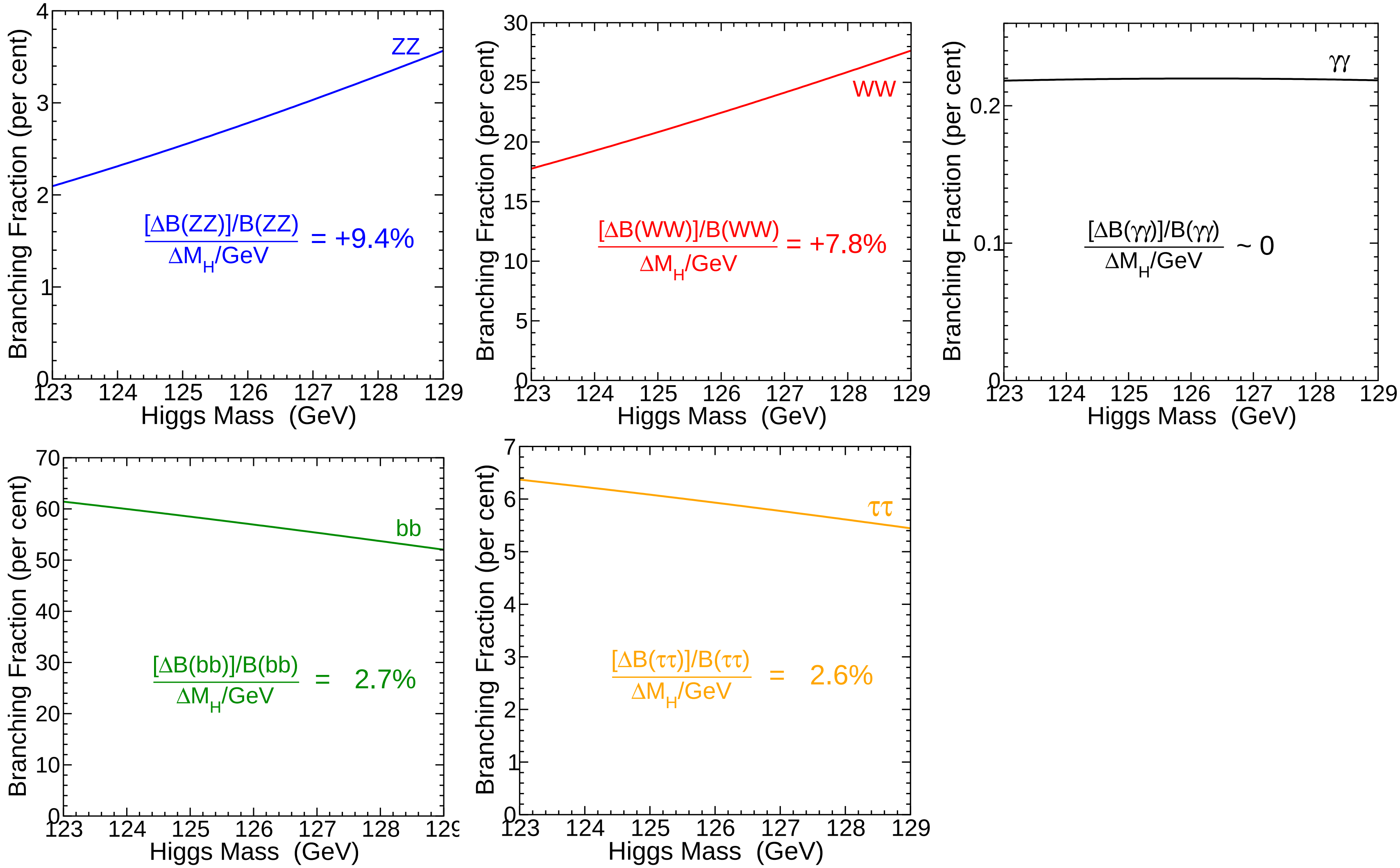
So, today I will.

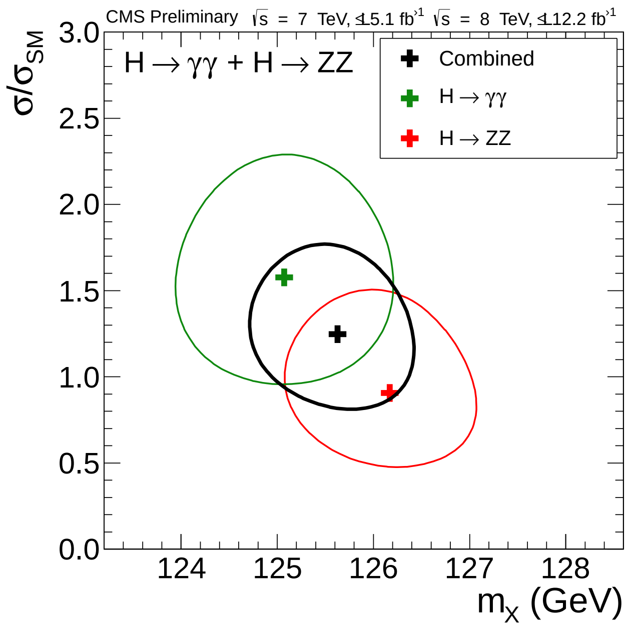
An intense program has already begun to learn about the couplings of H to other Standard Model states through its production and decays. Hopefully, this will eventually become a precision science.

Clearly, we also want to know M_H as accurately as possible.

- The last parameter in the (old) Standard Model
- Enters into precision EW fits
- Stability of the Standard Model vacuum
- Standard candle for future work (new physics decaying to H?)
- The Higgs branching ratios are sensitive to mass

Dependence of Higgs branching ratios on M_H, from HDECAY (Djouadi, Kalinowski, Spira):



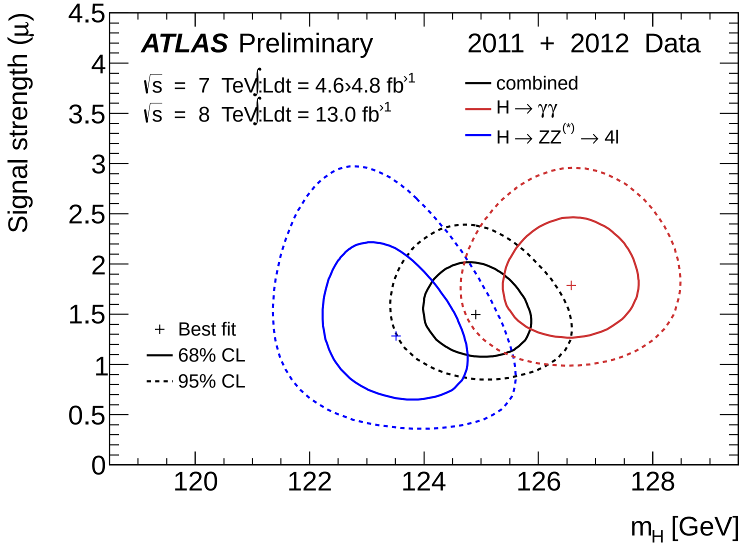


CMS M_H, stat, syst:

$125.1 \pm 0.4 \pm 0.6 \quad (H \to \gamma\gamma)$

$126.2 \pm 0.6 \pm 0.2 \quad (H \to ZZ)$

$125.8 \pm 0.4 \pm 0.4$ (combined)



ATLAS M_H:

$126.6 \pm 0.3 \pm 0.7 \quad (H \to \gamma\gamma)$

$123.5 \pm 0.8 \pm 0.3 \quad (H \to ZZ)$

$125.2 \pm 0.3 \pm 0.6$ (combined)

Need to confirm that $M_{H\to ZZ}$ and $M_{H\to\gamma\gamma}$ are really the same.

An interesting counterexample is:

“Mass-degenerate Higgs bosons at 125 GeV in the Two-Higgs-Doublet Model”, arXiv:1211.3131, P.M. Ferreira, H.E. Haber, R. Santos, J.P. Silva

They suggest that there could be two states near 126 GeV:

- A mostly SM-like Higgs that decays to both ZZ and $\gamma\gamma$,
- Another 0^+ or 0^- state that has suppressed coupling to ZZ, but still decays to $\gamma\gamma$

Expect $M_{H\to ZZ} \neq M_{H\to\gamma\gamma}$ and $\sigma_{\gamma\gamma} > \sigma_{ZZ}$.

But, note that so far ATLAS and CMS see opposite orderings for $M_{H\to ZZ}$ and $M_{H\to\gamma\gamma}$, compared to each other.

How well will LHC eventually be able to measure the Higgs mass?

Official estimates are hard to find. But...

Fabio Cerutti, representing ATLAS and CMS, at Higgs Factory Workshop, Fermilab November 2012:

- Approved LHC 300 fb^{-1} at 14 TeV: **Measure M_H to 100 MeV.**
- HL-LHC 3000 fb^{-1} at 14 TeV: **Measure M_H to 50 MeV.**

I don't know of an actual citeable study for this. The key is going to be systematics. Hard to know in advance. Meanwhile, lets be optimistic.

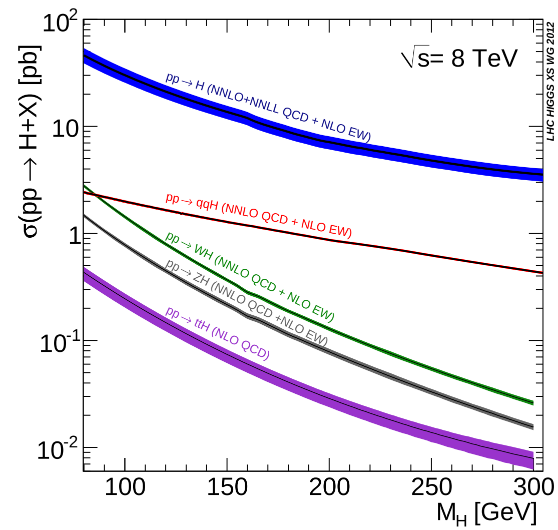
In this talk, consider the impact of quantum interference between the signal

$$gg \to H \to \gamma\gamma$$

and the continuum background with the same initial and final state.

Usually, interference between narrow-width resonant and continuum amplitudes can be safely neglected. However, in this case, the signal amplitude is loop-suppressed compared to the background amplitude.

Gluon fusion dominates the cross-section by more than an order of magnitude, but there is also a diphoton signal from VBF, with two taggable quark jets. This will **not** have the interference effect I'll discuss, since the initial and final states aren't the same.



Similarly, one expects the interference of $gg \to H \to ZZ$ with the continuum $gg \to ZZ$ background to be negligible.

This is because, unlike the loop-induced $H\gamma\gamma$ coupling, there is a HZZ coupling already at tree-level.

Don't have the requisite hierarchy of amplitudes:
(background) $\gg$ (signal).

For a precise determination of the Higgs mass, first define it.

Renormalized Higgs propagator:

$$\frac{i}{\hat{s} - m_H^2 - \Pi_H(\hat{s})} = \frac{iF_H(\hat{s})}{\hat{s} - M_H^2 + iM_H\Gamma_H},$$

- m_H is tree-level mass, Π_H is the 1PI self-energy function,
- $F_H(\hat{s})$ is slowly varying, with $F_H \approx 1$ in resonance region
- $M_H^2 - iM_H\Gamma_H$ = complex pole mass = gauge invariant

For most purposes, the narrow width approximation is used:

$$\frac{1}{(\hat{s}-M_H^2)^2+M_H^2\Gamma_H^2} \approx \frac{\pi}{M_H\Gamma_H}\delta(\hat{s}-M_H^2)$$

Because $\Gamma_H \approx 4.2$ MeV $\approx (3.4\times 10^{-5})M_H$, this is usually fine.
However, not for interference effects.

Instead, parameterize the cross-section by:

$$\frac{d\sigma_{pp\to\gamma\gamma+X}}{dm} = C(m) + \frac{1}{D(m)}[P(m) + (m^2 - M_H^2)I(m)]$$

where:

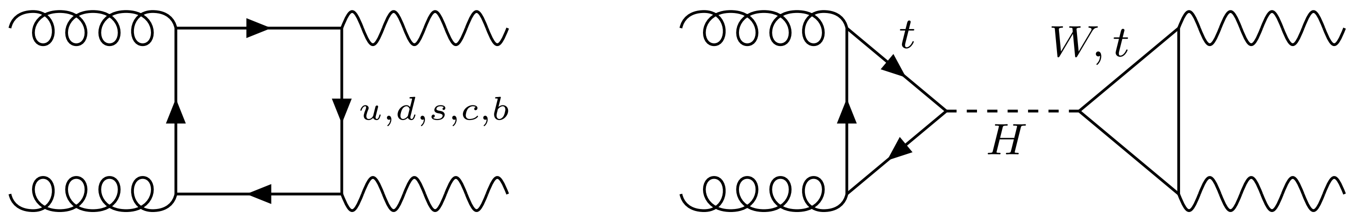
$$\begin{aligned} m &= \text{diphoton invariant mass,} \\ D(m) &= (m^2 - M_H^2)^2 + M_H^2\Gamma_H^2 \end{aligned}$$

$C(m)$ = continuum (non-Higgs),

$P(m)$ = resonance peak part (with small contribution from interference)

$I(m)$ = pure interference part.

Continuum and Higgs resonance amplitudes for $gg \to \gamma\gamma$:



$$\mathcal{M} \;=\; A_{gg\gamma\gamma} - \frac{A_{ggH} A_{\gamma\gamma H}}{\hat{s} - M_H^2 + i M_H \Gamma_H}$$

Because $M_H < 2M_W$, the imaginary parts of A_{ggH} and $A_{\gamma\gamma H}$ are small, coming from subdominant b, c, τ contributions:

$$\begin{aligned} A_{ggH} &= \frac{\alpha_S}{4\pi} M_H (0.337 + 0.013i) \\ A_{\gamma\gamma H} &= \frac{\alpha}{4\pi} M_H (-3.315 + 0.022i) \end{aligned}$$

Interference cross-section:

$$\Delta\sigma_{pp\to\gamma\gamma} \quad = \quad \int d\hat{s}\, G(\hat{s})\, \Delta\hat{\sigma}_{gg\to\gamma\gamma}$$

where $G(\hat{s})$ = gluon-gluon luminosity function, and

$$\begin{aligned}\Delta\hat{\sigma}_{gg\to\gamma\gamma} \quad &= \quad -\left[\frac{\hat{s}-M_H^2}{(\hat{s}-M_H^2)^2+M_H^2\Gamma_H^2}\right] 2\mathrm{Re}[A_{ggH}\,A_{\gamma\gamma H}\,A^*_{gg\gamma\gamma}] \\ &\quad\quad -\left[\frac{M_H\Gamma_H}{(\hat{s}-M_H^2)^2+M_H^2\Gamma_H^2}\right] 2\mathrm{Im}[A_{ggH}\,A_{\gamma\gamma H}\,A^*_{gg\gamma\gamma}]\end{aligned}$$

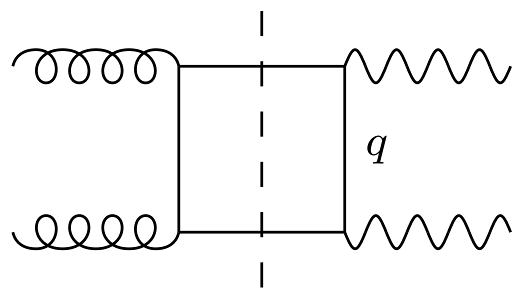
- First term vanishes after $\hat{s}$ integration in narrow-width approximation, because odd in $\hat{s}-M_H^2$.
- Second term small, because of Γ_H factor and because of quark mass suppression in $\mathrm{Im}[A_{gg\gamma\gamma}]$ at leading order for those polarizations that can interfere with H.

Dicus and Willenbrock 1988, Dixon and Siu 0302233

Showing dependence on gluon polarizations λ_1, λ_2 and photon polarizations λ_3, λ_4 explicitly:

$$\mathcal{M} = 4\alpha\alpha_S \sum_{q=u,d,s,c,b,t} e_q^2 M^q_{\lambda_1\lambda_2\lambda_3\lambda_4} - \delta_{\lambda_1\lambda_2}\delta_{\lambda_3\lambda_4} \frac{A_{ggH}A_{\gamma\gamma H}}{\hat{s} - M_H^2 + iM_H\Gamma_H}$$

Since $\hat{s} \approx M_H^2 \gg m^2_{u,d,s,c,b}$, one might expect large imaginary parts for the continuum amplitudes. Indeed, there are:



However, for the particular polarizations M^q_{++++}, M^q_{++--}, M^q_{--++}, M^q_{----} that can interfere with the Higgs resonance, the imaginary parts happen to be suppressed by $m_q^2/\hat{s}$.

Dicus and Willenbrock 1988

In the $m_q^2/\hat{s} \to 0$ limit:

$$M^q_{++--} = M^q_{--++} = 1,$$
$$M^q_{++++} = M^q_{----} = -1 + z \ln\left(\frac{1+z}{1-z}\right) - \frac{1+z^2}{4}\left[\ln^2\left(\frac{1+z}{1-z}\right) + \pi^2\right],$$

where $z = \cos\theta$ in the $\gamma\gamma$ COM frame. Karplus+Neuman 1951

- Top-quark amplitude is suppressed by $\hat{s}^2/m_t^4$.
- Full mass dependences for c, b, t included in following; don't make huge difference.
- The $M^q_{++++} = M^q_{----}$ amplitude is forward/backward peaked $(z = \pm 1)$, while the Higgs amplitude is isotropic. Will return to this later.

There are two orthogonal issues for signal/background interference:

- **Contribution of interference to total $H \to \gamma\gamma$ cross-section.** Dixon and Siu 0302233 showed that the leading effect arises from the 2-loop order correction to the continuum amplitude, where the mass suppression found for the relevant polarizations at 1-loop order are absent. I will briefly review their results first.

- **Contribution of interference to $H \to \gamma\gamma$ mass distribution.** After experimental resolution effects, there remains a small but (eventually) measurable effect.

Dixon and Siu 0302233

Fractional interference correction to cross-section (neglect real part):

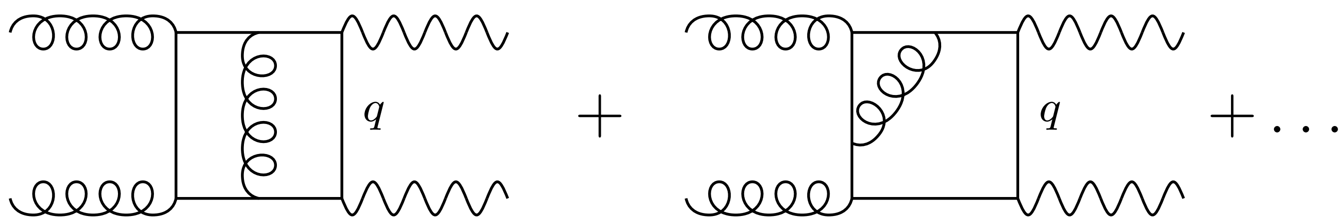
$$\frac{\Delta\hat{\sigma}}{\hat{\sigma}} = 2M_H\Gamma_H \,\mathrm{Im}\left[\frac{A^{(1)}_{gg\gamma\gamma}}{A^{(1)}_{ggH}A^{(1)}_{\gamma\gamma H}}\left(1+\frac{A^{(2)}_{gg\gamma\gamma}}{A^{(1)}_{gg\gamma\gamma}}-\frac{A^{(2)}_{ggH}}{A^{(1)}_{ggH}}-\frac{A^{(2)}_{\gamma\gamma H}}{A^{(1)}_{\gamma\gamma H}}\right)\right]$$

Here, $^{(n)}$ means n-loop contribution.

Black term is the dominant one.

While $\mathrm{Im}[A^{(2)}_{g^-g^-\gamma^+\gamma^+}]$ still goes like $m_q^2/\hat{s}$, just like at 1-loop, there is no suppression in $\mathrm{Im}[A^{(2)}_{g^+g^+\gamma^+\gamma^+}]$.

The required 2-loop amplitudes were computed by Bern, DeFreitas and Dixon, 0109078, in the $m_q^2/\hat{s} \to 0$ limit:

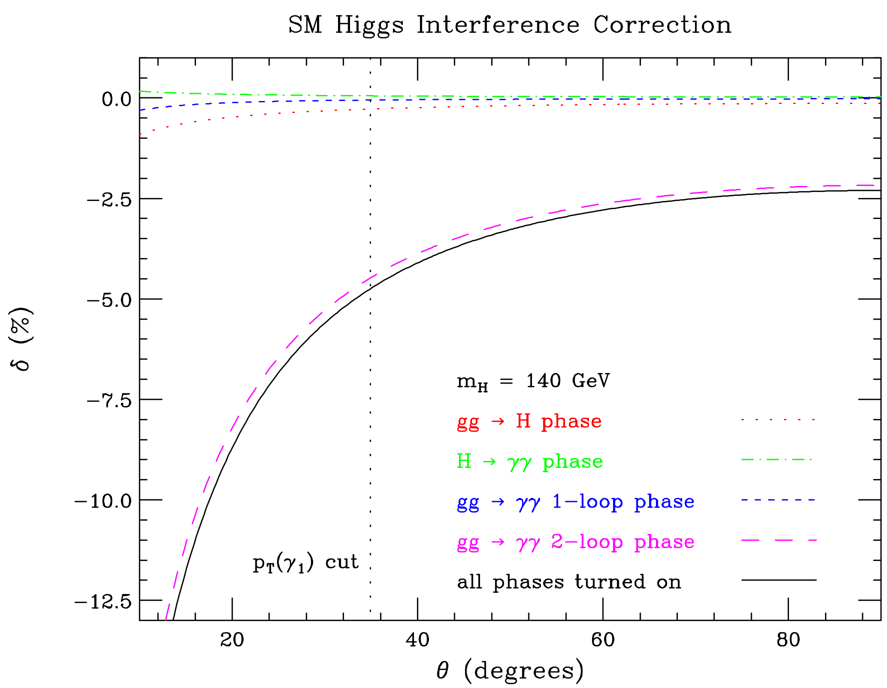


in terms of polylogs involving the scattering angle θ.

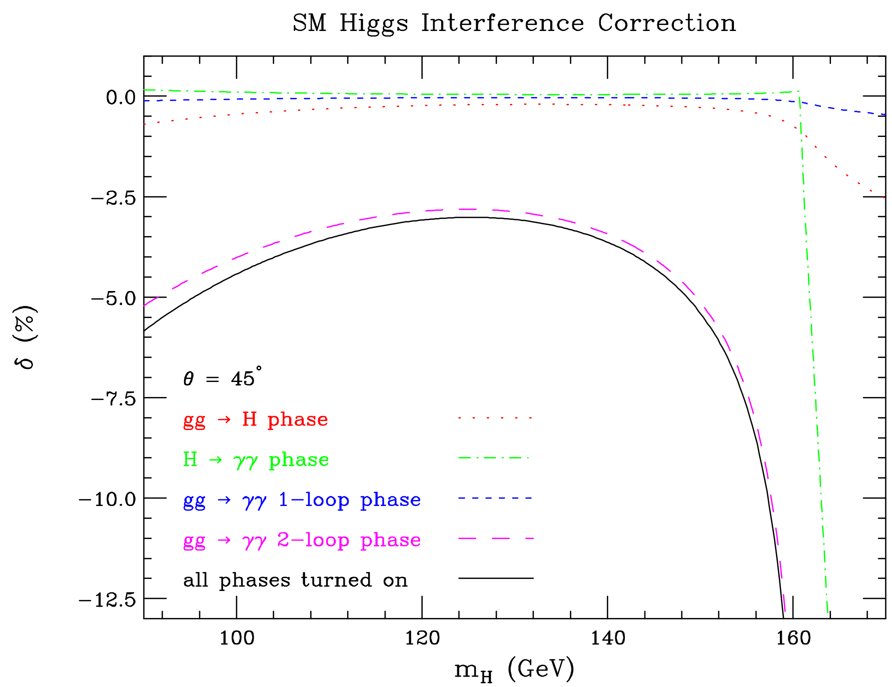
The imaginary part of the amplitude for the $++++$ configuration is again forward/backward peaked.

Dixon and Siu 0302233

$M_H = 140$ GeV, varying θ:



$\theta = 45°$, varying M_H:



Interference is negative for the total (integrated over the lineshape) cross-section, and of order 2% to 5% depending on the Higgs-frame scattering angle.

Now return to the shape of the $\gamma\gamma$ mass distribution.

$$\frac{d^2\sigma^{H,\,\mathrm{resonant}}_{pp\to\gamma\gamma}}{d(\sqrt{\hat{s}})dz} = \frac{G(\hat{s})}{128\pi\sqrt{\hat{s}}}|A_{ggH}A_{\gamma\gamma H}|^2\left[\frac{1}{(\hat{s}-M_H^2)^2+M_H^2\Gamma_H^2}\right]$$
$$\frac{d^2\sigma^{\mathrm{int}}_{pp\to\gamma\gamma}}{d(\sqrt{\hat{s}})dz} = -\frac{G(\hat{s})}{64\pi\sqrt{\hat{s}}}\mathrm{Re}[A_{ggH}A_{\gamma\gamma H}A^*_{gg\gamma\gamma}]\left[\frac{\hat{s}-M_H^2}{(\hat{s}-M_H^2)^2+M_H^2\Gamma_H^2}\right]$$

The interference leads to a surplus of events for $\hat{s} < M_H^2$ and a deficit for $\hat{s} < M_H^2$, shifting the $\gamma\gamma$ mass distribution.

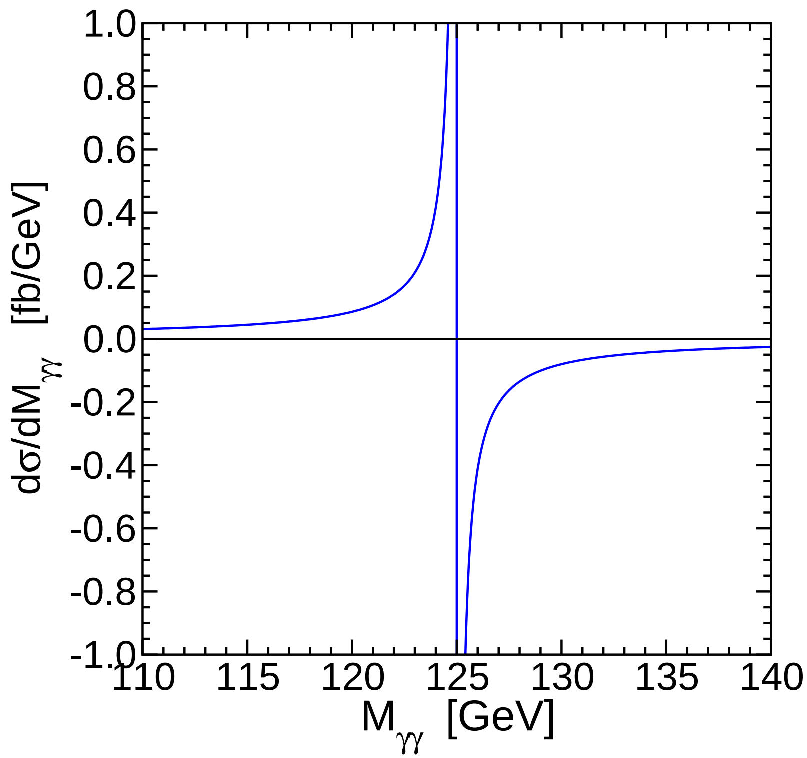
Because

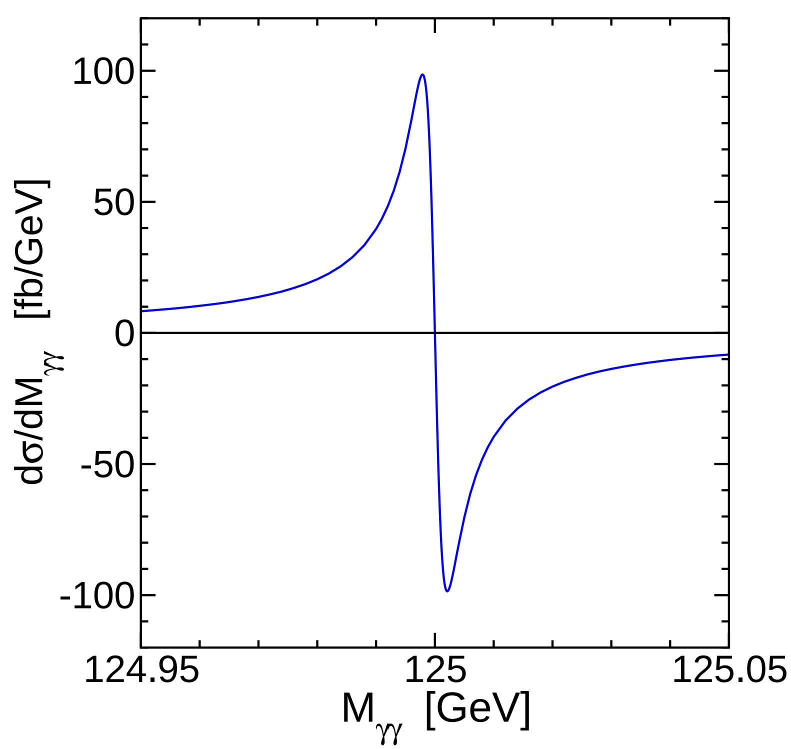
$$G(\hat{s},s,Q^2) = \int_{\hat{s}/s}^{1}\frac{dx}{sx}\,g(x,Q^2)g(\hat{s}/sx,Q^2)$$

appears in front of both resonant and interference, the change in the shape (as opposed to size) of the diphoton mass distribution is nearly scale-independent at LO.

Interference contribution, before including experimental resolution:

close-up:

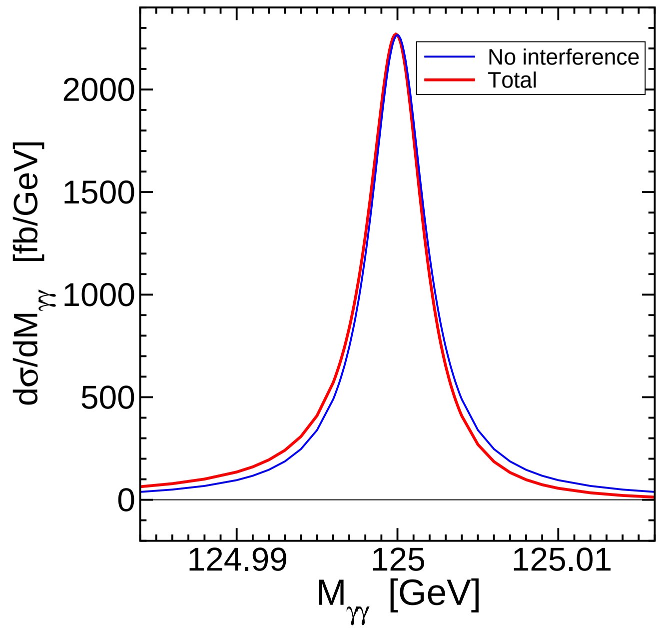


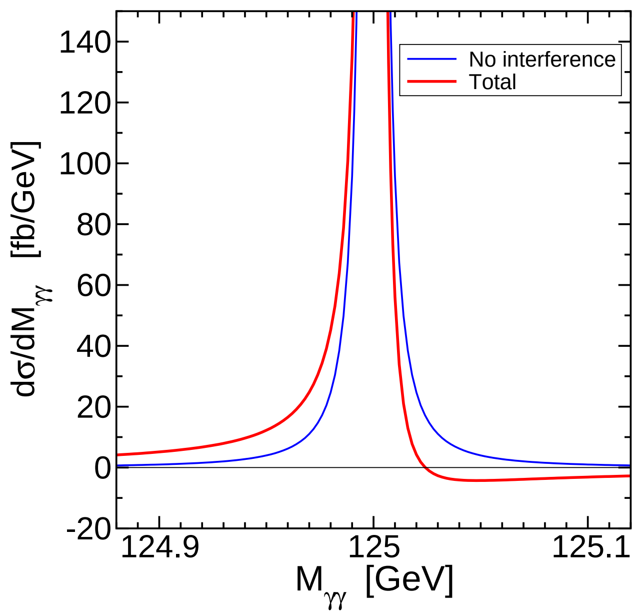


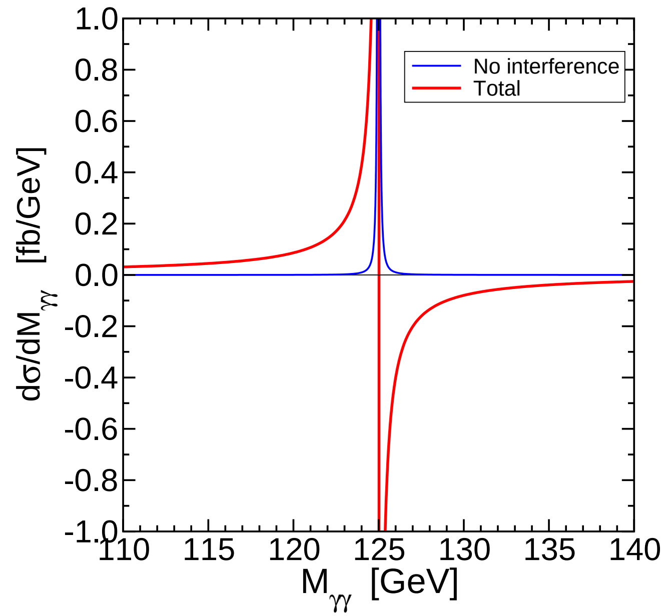
There is a very sharp peak/dip with maximum at $M_H - \Gamma_H/2$ and minimum at $M_H + \Gamma_H/2$. Much, but not all of this structure is washed out by detector resolution effects.

Signal with and without interference, **before smearing**.

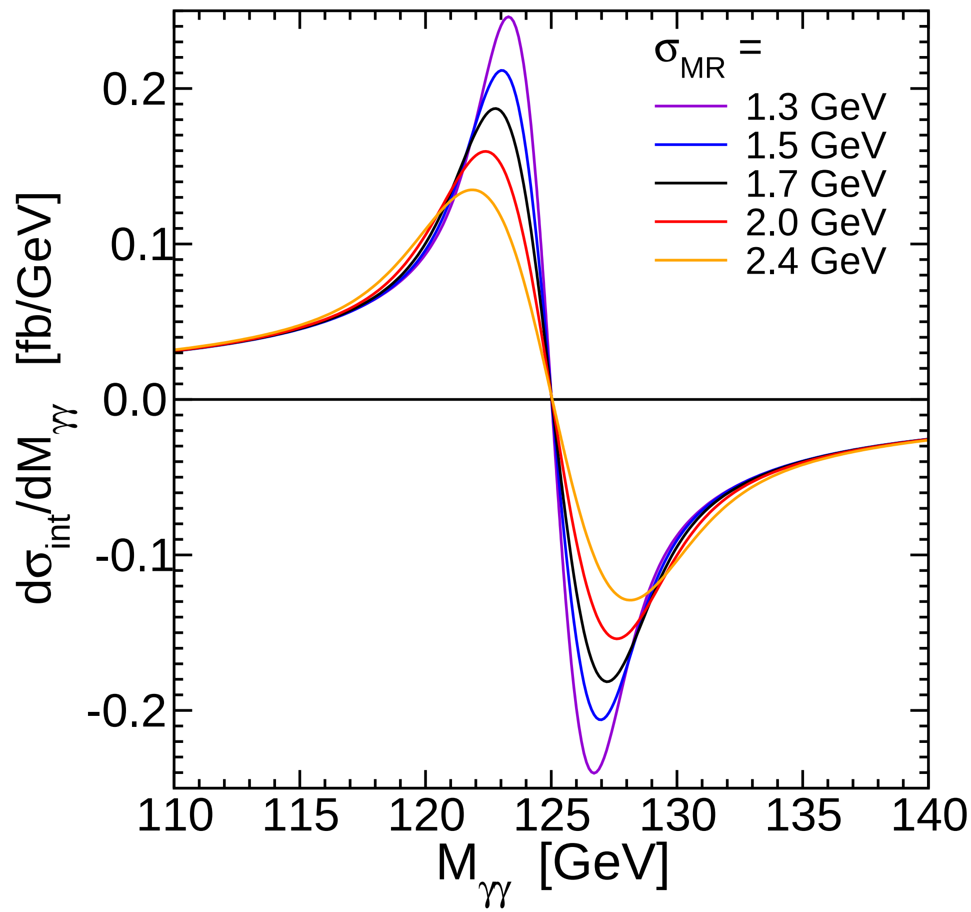
These are all exactly the same plot, just with different scales on the axes.







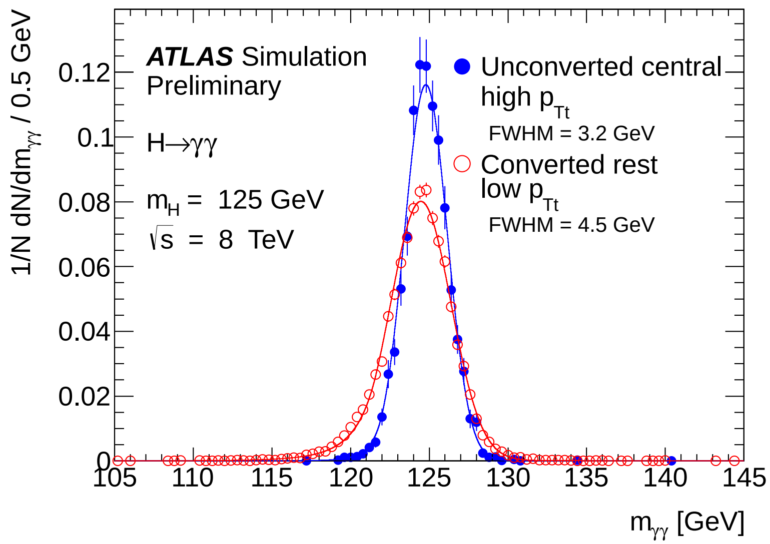
Now, the interference after smearing by various Gaussian mass resolutions:



The Gaussian smearing is used as a rough approximation to the real world situation, where the diphoton mass response is different in different parts of the detectors, depends on photon conversions, and is certainly not quite Gaussian. . .

ATLAS and CMS each have multiple different categories of events, with different model responses to a diphoton signal line depending on position in the detector, conversion of photons, and other objects in event. Not Gaussian; low mass tail.

Two examples from ATLAS:



ATLAS models with a "Crystal Ball" lineshape, dependent on 4 parameters σ_{CB}, α, n, δ_{M_H}.

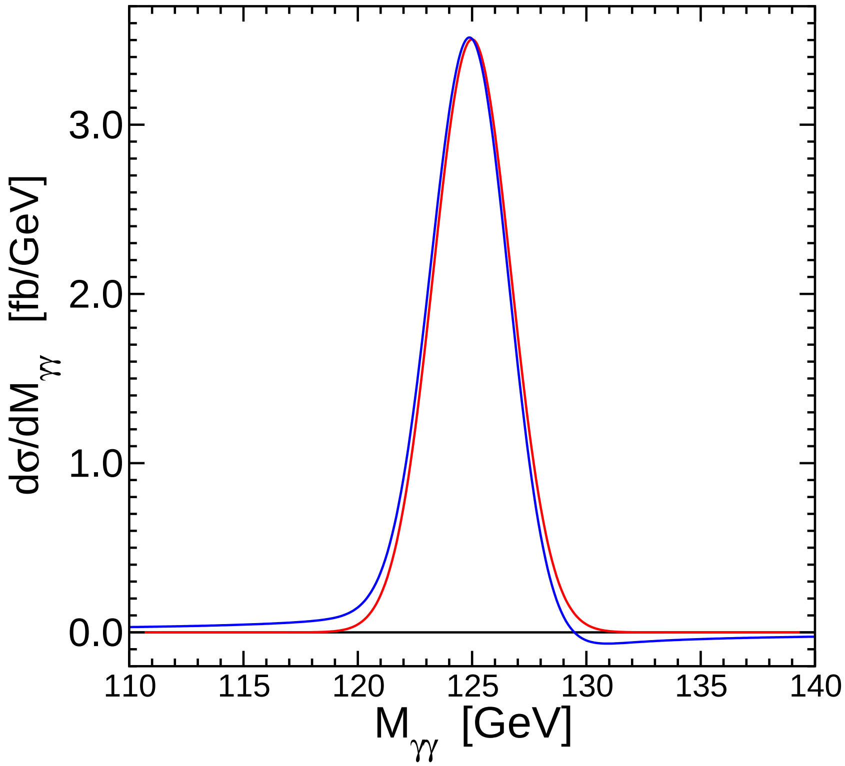
$$Ne^{-t^2/2} \qquad \text{(if } t > -\alpha\text{)}$$

$$N'(n/\alpha - \alpha - t)^{-n} \qquad \text{(if } t > -\alpha\text{).}$$

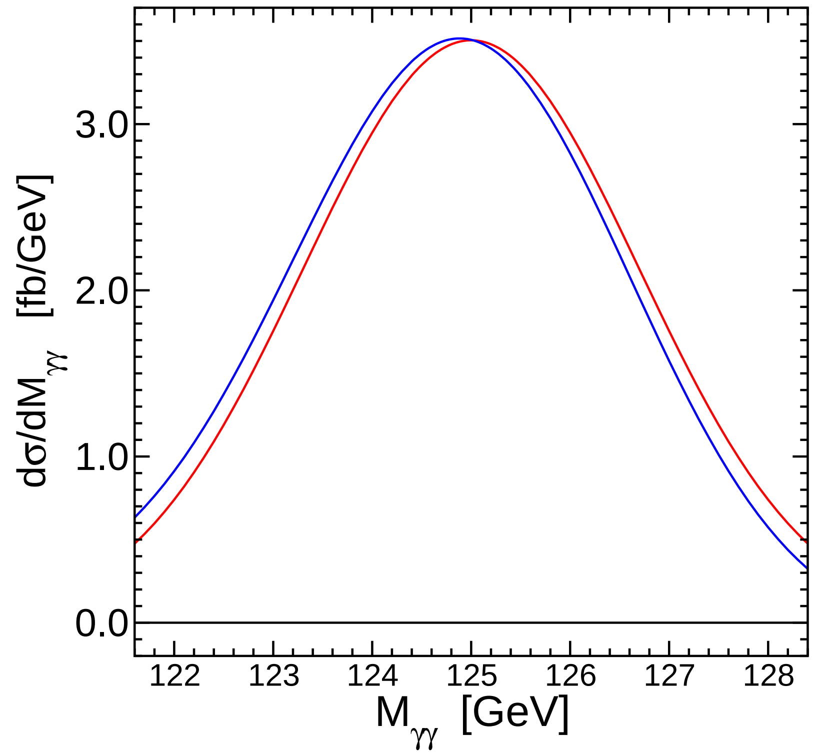
Here $t = (M_{\gamma\gamma} - M_H - \delta_{M_H})/\sigma_{CB}$.

Too complicated and mysterious for theorists (me) to model correctly. I use pure Gaussian instead; results should be qualitatively similar.

Compare signal with and without interference: (for $\sigma_{\mathrm{MR}} = 1.7$ GeV)



close-up:



By eyeball, the shift is of order $\Delta M_{\gamma\gamma} \sim -200$ MeV.

To be more precise will depend crucially on exactly how the distribution is fitted. (Not simple, not the same for ATLAS and CMS!)

The shift doesn't depend significantly on Γ_H, as long as $\Gamma_H \ll \sigma_{\rm MR}$.

Using a different prescription for the lineshape, such as the "running width" prescription

$$\frac{1}{(\hat{s}^2 - M_H^2)^2 + M_H^2 \Gamma_H^2} \quad \to \quad \frac{1}{(\hat{s}^2 - M_H^2)^2 + \hat{s}[\Gamma_H(\hat{s})]^2}$$

will give same results.

After experimental resolution, the Higgs width is nearly irrelevant for $\gamma\gamma$, provided it is small.

This is in contrast to other work on Higgs interference for M_H above the WW threshold, where large Γ_H can be important. (Glover and ven der Bij 1989; Campbell, Ellis, Williams 1107.5569, Kauer, Passarino 1206.4803, Passarino 1206.3824.)

A crude theoretical measure of the mass shift (not practical or realistic!)

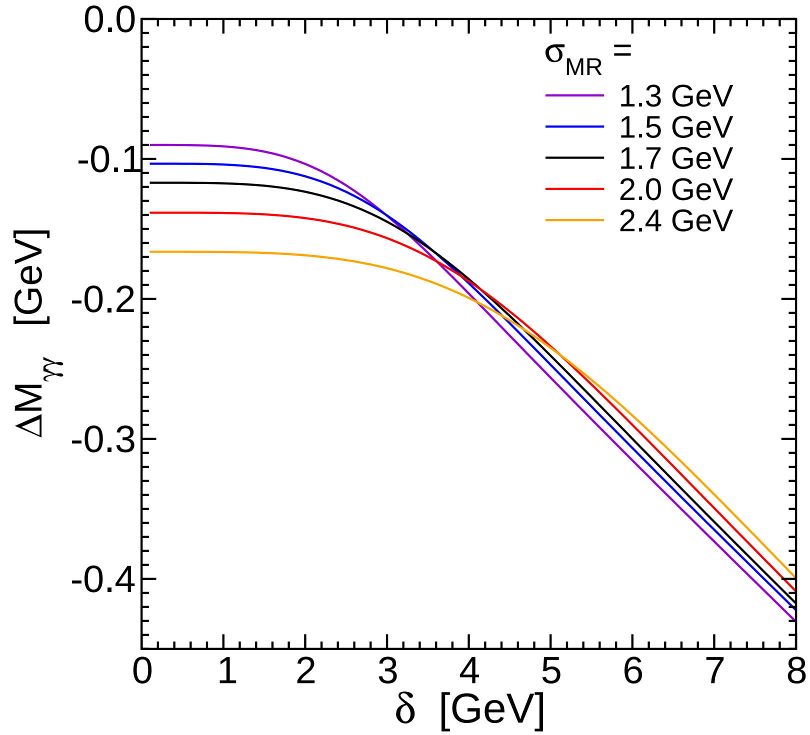
- Define $M_{\rm peak}$ as the maximum of the distribution
- Choose a mass window $|M_{\gamma\gamma} - M_{\rm peak}| < \delta$
- Compute

$$
\begin{aligned}
N_\delta &= \int_{M_{\rm peak}-\delta}^{M_{\rm peak}+\delta} dM_{\gamma\gamma} \frac{d\sigma}{dM_{\gamma\gamma}}, \\
\langle M_{\gamma\gamma} \rangle_\delta &= \frac{1}{N_\delta} \int_{M_{\rm peak}-\delta}^{M_{\rm peak}+\delta} dM_{\gamma\gamma}\, M_{\gamma\gamma}\, \frac{d\sigma}{dM_{\gamma\gamma}}.
\end{aligned}
$$

- Define the mass shift as:

$$\Delta M_{\gamma\gamma} \equiv \langle M_{\gamma\gamma} \rangle_{\delta,\,\text{total}} - \langle M_{\gamma\gamma} \rangle_{\delta,\,\text{no interference}}$$

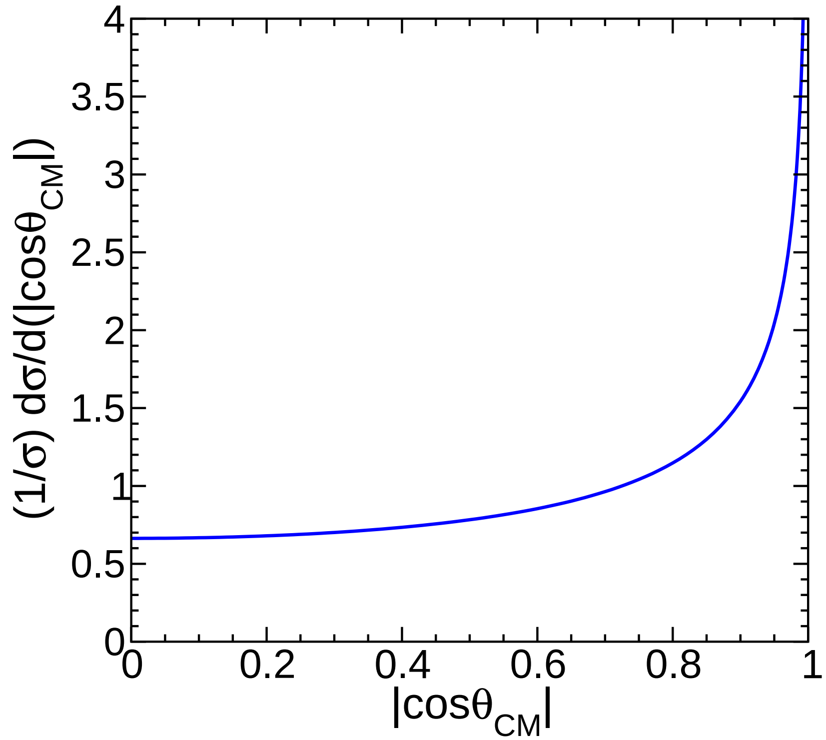
Shift as defined by $\Delta M_{\gamma\gamma}$, for various Gaussian mass resolutions:



- For small $\delta < 3$ GeV: $\Delta M_{\gamma\gamma}$ just measures the shift in the peak value. Surprisingly, larger for worse mass resolution.
- For large $\delta > 2\sigma_{\rm MR}$: $\Delta M_{\gamma\gamma}$ grows linearly with δ, due to long $\sqrt{\text{Breit-Wigner}}$ tail.
- For a sensible intermediate value like $\delta = 4$ GeV, shift is about 200 MeV, with relatively small dependence on $\sigma_{\rm MR}$.

So far, have considered only total $d\sigma/dM_{\gamma\gamma}$. However, experimental cuts and detector efficiencies favor the central regions of detectors, while the interference part is peaked forward/backward.

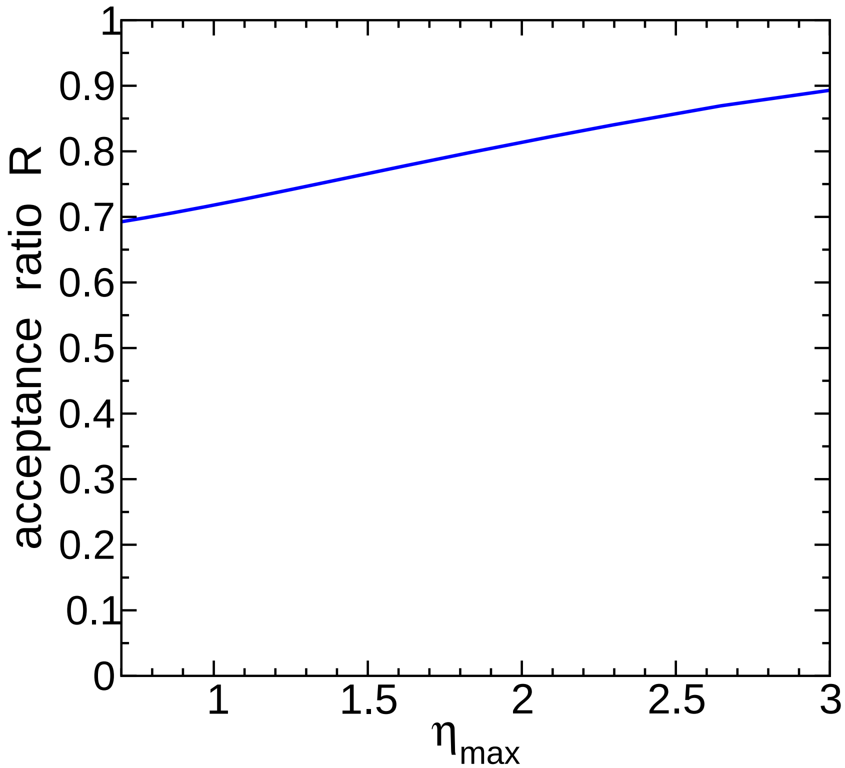
Angular distribution of interference in the $\gamma\gamma$ CM frame:



The "pure" Higgs resonance has a flat (isotropic) distribution.

Translate into lab-frame cut $|\eta| < \eta_{\rm max}$, using ratio of acceptances:

$$R = (\sigma_{\rm cut}^{\rm int}/\sigma_{\rm total}^{\rm int})/(\sigma_{\rm cut}^{H}/\sigma_{\rm total}^{H})$$



ATLAS: $\eta_{\rm max} = 2.37$, except for $1.37 < |\eta| < 1.52$.

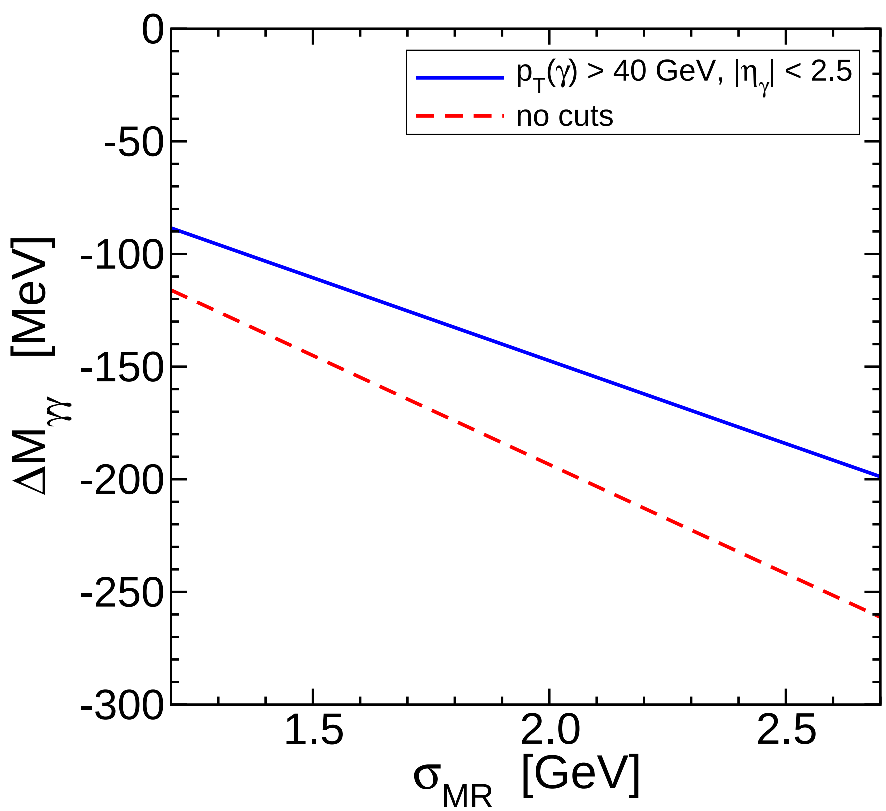
CMS: $\eta_{\rm max} = 2.5$, except for $1.44 < |\eta| < 1.57$.

Both also cut on photon p_T's (somewhat correlated), and have variable efficiencies. A LO analysis can't accurately capture these effects.

After semi-realistic parton-level cuts:

- $p_T(\gamma) > 40$ GeV,
- $|\eta_\gamma| < 2.5$,

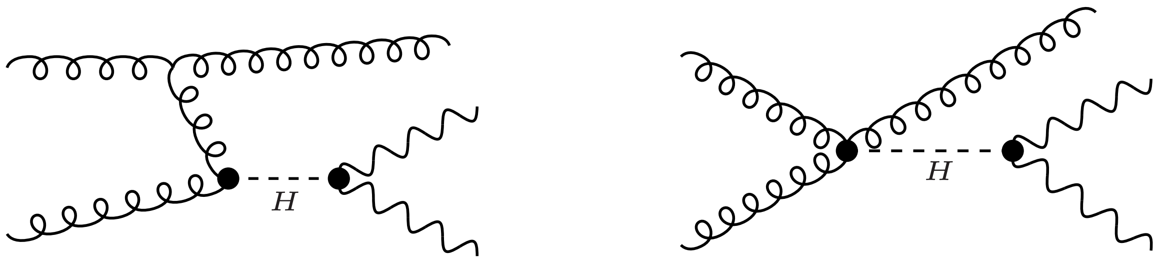
the shift $\Delta M_{\gamma\gamma}$ as a function of $\sigma_{\rm MR}$, obtained by simple fits to Gaussians with same width used to do the smearing:



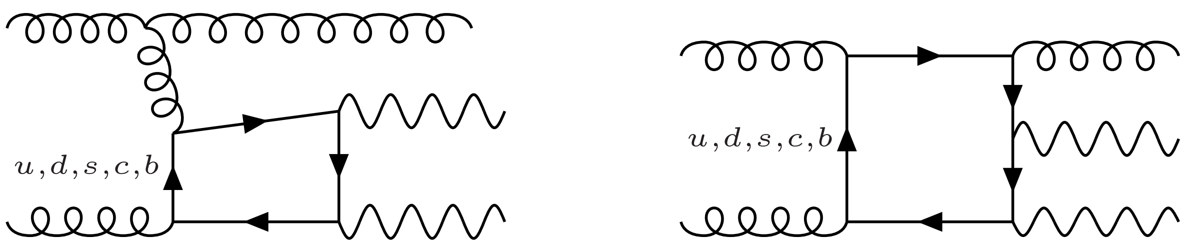
Shift increases with $\sigma_{\rm MR}$.

Now consider interference for $pp \to jH$, with a p_T cut on the jet.

$gg \to Hg \to g\gamma\gamma$:

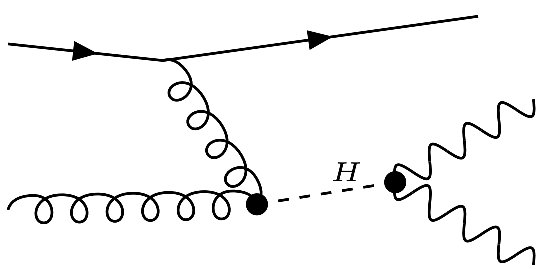


interfere with

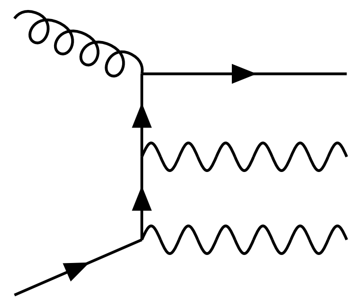


Also have parton-level processes initiated by quarks.

$gq \to qH \to q\gamma\gamma$ and $q\overline{q} \to gH \to g\gamma\gamma$



interferes with

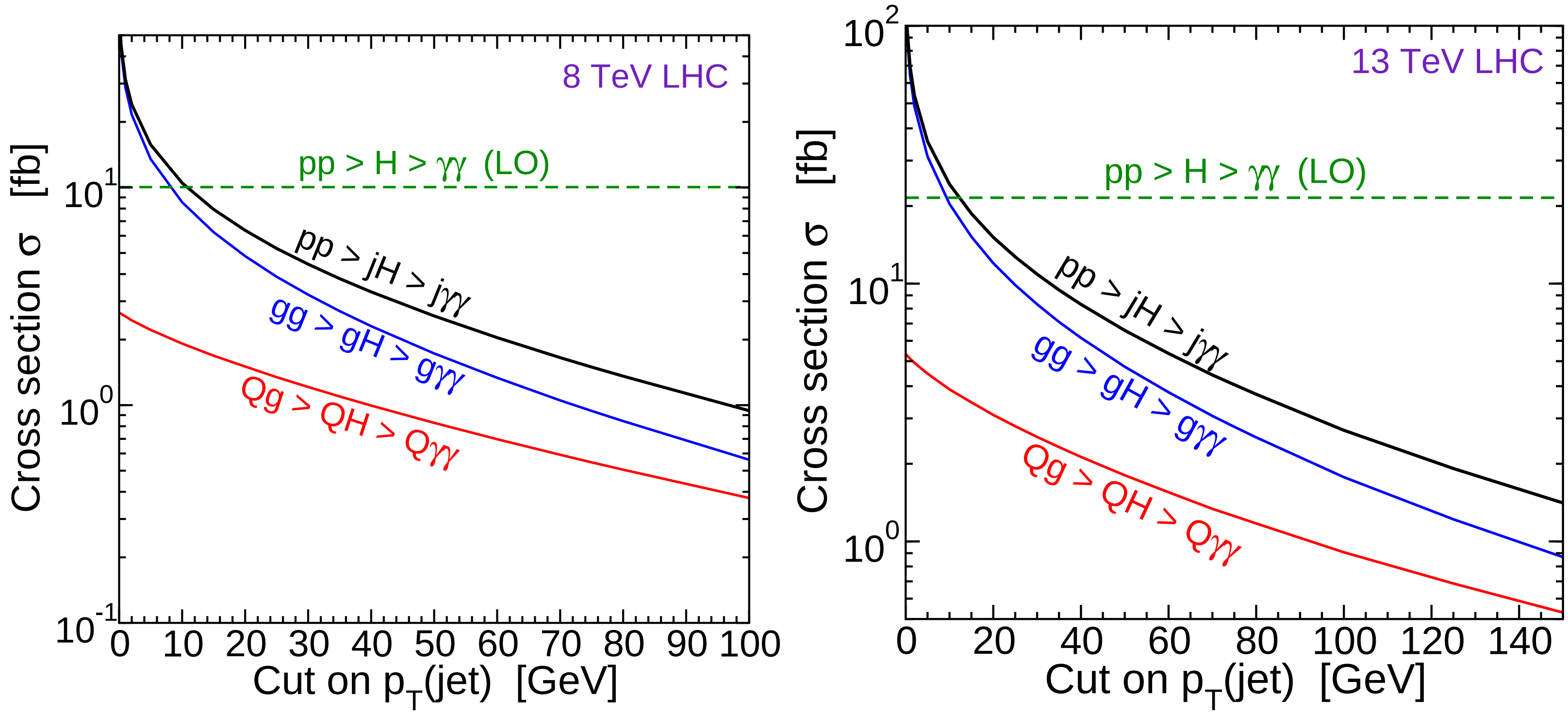


Here the background is tree-level, so that the Higgs-background interference is naively **more** important compared to the pure Higgs signal. But quark PDFs are much smaller.

Buenos Aires group of de Florian, Fidanza, Hernández-Pinto, Mazzitelli, Rotstein-Habarnau, and Sborlini have also done this (using different methods), in `1303.1397`. We agree: mass shift goes other direction!

This agrees with Martin’s Theorem.

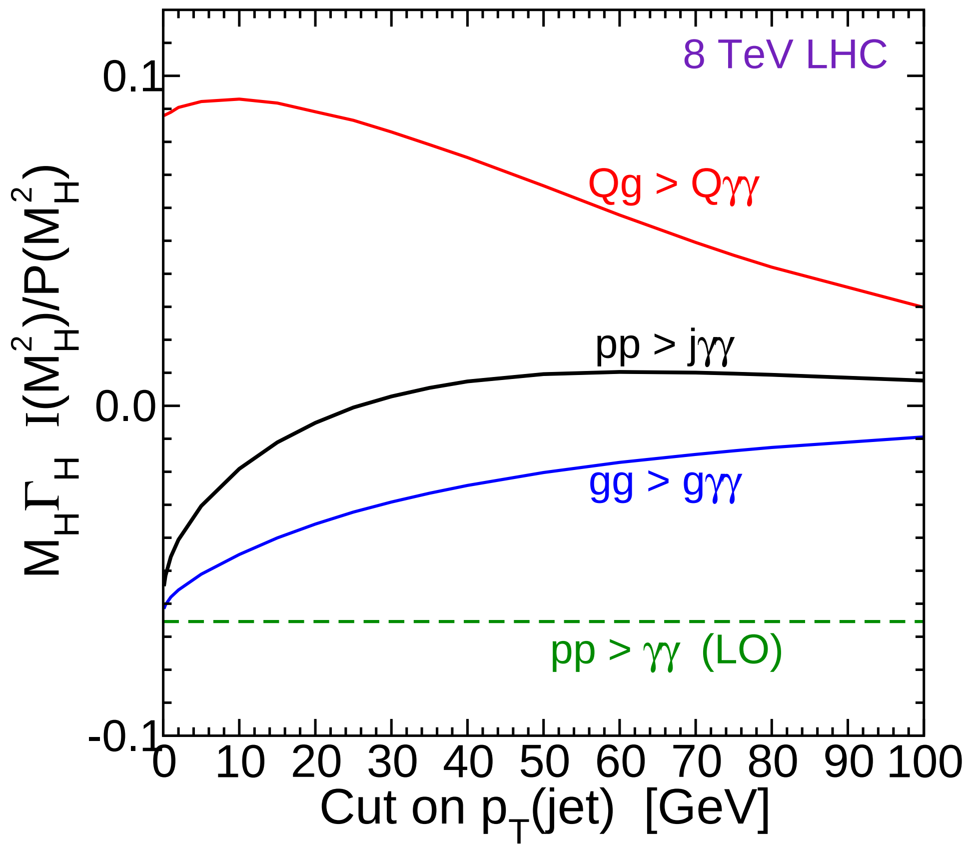
Cross-sections as a function of the cut on p_T^j:



Infrared log divergences from small p_T^j need to be regularized and cancelled against divergences in virtual corrections to LO process (without jet). Not done yet. Shouldn't take $p_T^j < 15$ GeV seriously.

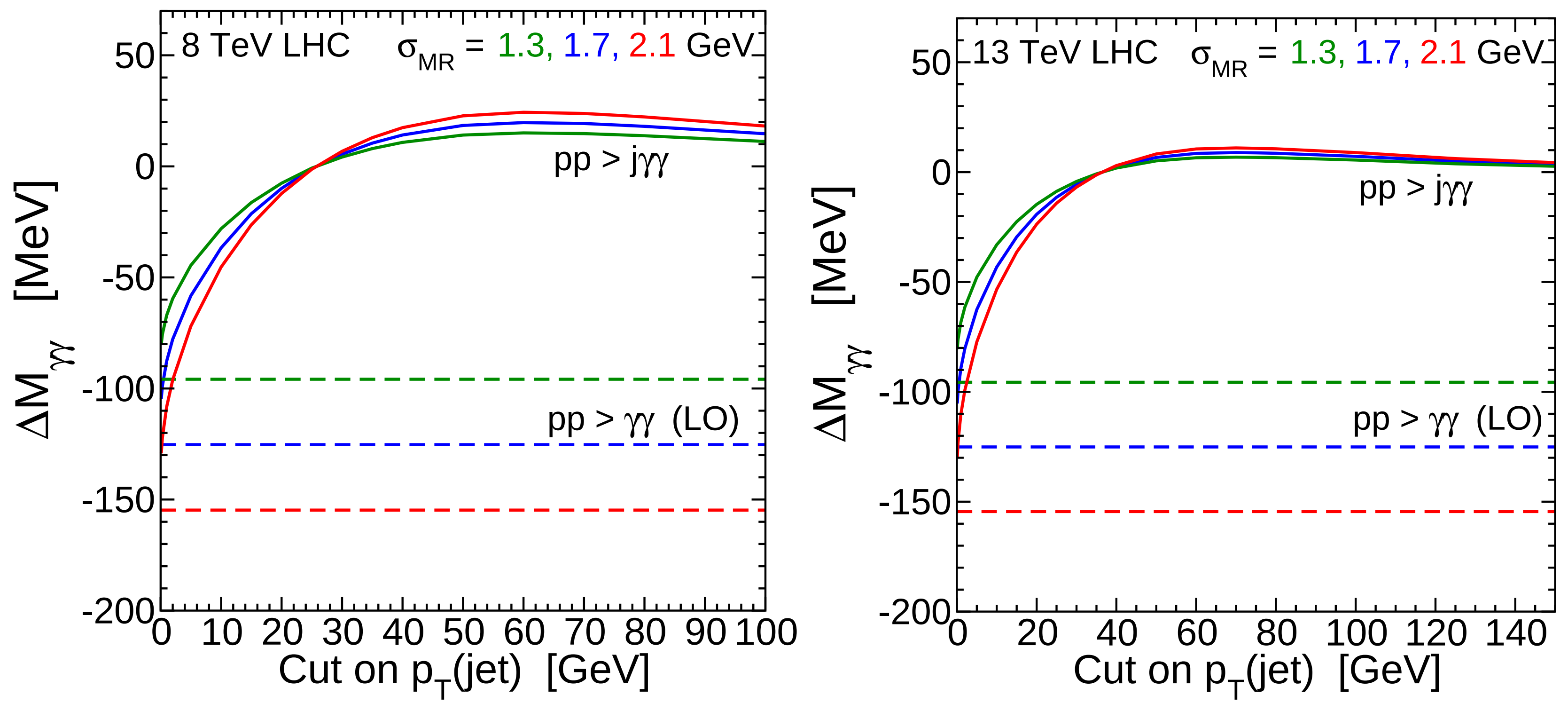
However, that region is formally useful, because the results for the mass shift should go over to the LO (no-extra-jet) case.

A measure of the relative importance of the interference term compared to the background, which is independent of experimental mass resolution:



I applied cuts $p_T(\gamma_1) > 40$ GeV, $p_T(\gamma_1) > 30$ GeV, $|\eta_\gamma| < 2.5$, $\Delta D_{j\gamma} > 0.4$, $\Delta D_{\gamma\gamma} > 0.4$, all at parton level.

Diphoton mass peak shift, as a function of the cut on p_T^j:



Very small, and positive shift for any reasonable cut on p_T^j.

Outlook

- Interference with background can shift the position of the Higgs diphoton mass peak by perhaps about -100 to -150 MeV for events with no central jet, and 0 to $+20$ MeV for events with a central jet. Not huge, but probably significant compared to the eventual uncertainty, and larger than the last significant digit being reported even today.

- The actual mass shift will depend on the specific methods used for the fit. The experimental collaborations would have to do this themselves to get a more precise value. (The methods I used to fit for the mass shift are certainly not practical, or realistic.)

- The VBF diphoton and $ZZ \to 4l$ mass distributions should be nearly unaffected by interference with background.

- A full NLO Monte Carlo generator is needed.